

# Extraction of $R = \frac{\sigma_L}{\sigma_T}$ from CCFR $\nu_\mu$ -Fe and $\bar{\nu}_\mu$ -Fe differential cross sections

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We report on the extraction of  $R = \frac{\sigma_L}{\sigma_T}$  from CCFR  $\nu_\mu$ -Fe and  $\bar{\nu}_\mu$ -Fe differential cross sections. The CCFR differential cross sections do not show the deviations from the QCD expectations that are seen in the CDHSW data at very low and very high  $x$ .  $R$  as measured in  $\nu_\mu$  scattering is in agreement with  $R$  as measured in muon and electron scattering. All data on  $R$  for  $Q^2 > 1 \text{ GeV}^2$  are in agreement with a NNLO QCD calculation which uses NNLO PDFs and includes target mass effects. We report on the first measurements of  $R$  in the low  $x$  and  $Q^2 < 1 \text{ GeV}^2$  region (where an anomalous large rise in  $R$  for nuclear targets has been observed by the HERMES collaboration).

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The ratio of longitudinal and transverse structure function,  $R (=F_L/2xF_1)$  in deep inelastic lepton-nucleon scattering experiments is a sensitive test of the quark parton model of the nucleon. In leading order QCD,  $R$  for the scattering from spin 1/2 constituents (e.g. quarks) is zero, while  $R$  for the scattering from spin 0 or spin 1 constituents is very large. The small value of  $R$  originally measured in electron scattering experiments [1] provided the initial evidence for the spin 1/2 nature of the nucleon constituents. However, a non-zero value of  $R$  can also originate from processes in which the struck quark has a finite transverse momentum. These include Quantum Chromodynamics (QCD) processes involving emissions of gluons, processes involving the production of heavy quarks, target mass [2] corrections and higher twist effects [3,4]. Recently, there has been a renewed interest in  $R$  at small values of  $x$  and  $Q^2$ , because of the large anomalous nuclear effect that has been reported by the HERMES experiment [5]. A large value of  $R$  in nuclear targets could be interpreted as evidence for non spin 1/2 constituents, such as  $\rho$  mesons in nuclei [6]. In this letter, we report on an extraction of  $R$  in neutrino scattering ( $R^\nu$ ), extending to low  $x$  and  $Q^2$ . We also compare the CCFR differential cross sections with previous CDHSW [7]  $\nu_\mu$ -Fe and  $\bar{\nu}_\mu$ -Fe data.

Previous measurements of  $R$  in muon and electron scattering ( $R^{\mu/e}$ ) were fit using  $R_{world}^{\mu/e}$  [8] (a QCD inspired empirical form). The  $R_{world}^{\mu/e}$  fit is also in good agreement with recent NMC muon data [9] for  $R$  at low  $x$ , and with theoretical predictions [4]  $R_{NNLO+TM}^{\mu/e}$  (a Next to Next to Leading (NNLO) QCD calculation using NLO Parton Distribution Functions (PDFs), and including target mass effects). Very recently the NNLO-QCD calculations for  $F_L$  have been updated [10] to include estimates of the contribution from NNLO PDFs. In addition, the NLO-QCD calculations have been updated to include  $\ln(1/x)$  resummation terms [11] which are important at small  $x$ . A full QCD calculation which includes both the NNLO and the  $\ln(1/x)$  resummation terms is not yet available. We evaluate  $R_{NNLOpdfs+TM}^{\mu/e}$  and  $R_{NNLOresum+TM}^{\mu/e}$  by adding target mass effects to these calculations of  $F_L$ .

For  $x > 0.1$  it is expected that  $R^\nu$  should be the same as  $R^{\mu/e}$ . However, for  $x < 0.1$  and low  $Q^2$  (in leading order),  $R^\nu$  is expected to be larger than  $R^{\mu/e}$  because of the production of massive charm quarks in the final state. We calculate [12] a correction to  $R_{world}^{\mu/e}$  for this difference using a leading order slow rescaling model with a charm mass,  $m_c (= 1.3 \text{ GeV})$  and obtain an effective

$R_{world}$  for  $\nu_\mu$  scattering ( $R_{eff}^\nu$ ). Our measurements of  $R^\nu$  are compared to  $R^{\mu/e}$  data and also to predictions from  $R_{eff}^\nu$ ,  $R_{world}^{\mu/e}$ ,  $R_{NNLOpdfs+TM}^{\mu/e}$ , and  $R_{NLOresum+TM}^{\mu/e}$ .

Values of  $R$  are extracted from the sum of  $\nu_\mu$  and  $\bar{\nu}_\mu$  differential cross sections for charged current interactions on isoscalar target using following relation:

$$F(\epsilon) \equiv \left[ \frac{d^2\sigma^\nu}{dx dy} + \frac{d^2\sigma^{\bar{\nu}}}{dx dy} \right] \frac{(1-\epsilon)\pi}{y^2 G_F^2 M E_\nu} \\ = 2xF_1[1 + \epsilon R] + \frac{y(1-y/2)}{1+(1-y)^2} \Delta x F_3, \quad (1)$$

where  $G_F$  is the weak Fermi coupling constant,  $M$  is the nucleon mass,  $E_\nu$  is the incident energy, the scaling variable  $y = E_h/E_\nu$  is the fractional energy transferred to the hadronic vertex,  $E_h$  is the final state hadronic energy, and  $\epsilon \simeq 2(1-y)/(1+(1-y)^2)$  is the polarization of virtual  $W$  boson. The structure function  $2xF_1$  is expressed in terms of  $F_2$  by  $2xF_1(x, Q^2) = F_2(x, Q^2) \times \frac{1+4M^2x^2/Q^2}{1+R(x, Q^2)}$ , where  $Q^2$  is the square of the four-momentum transfer to the nucleon,  $x = Q^2/2ME_h$  (the Bjorken scaling variable) is the fractional momentum carried by the struck quark. Here  $\Delta x F_3 = xF_3^\nu - xF_3^{\bar{\nu}}$ , which in leading order  $\simeq 4x(s - c)$  (difference between the strange and charm quark distributions).

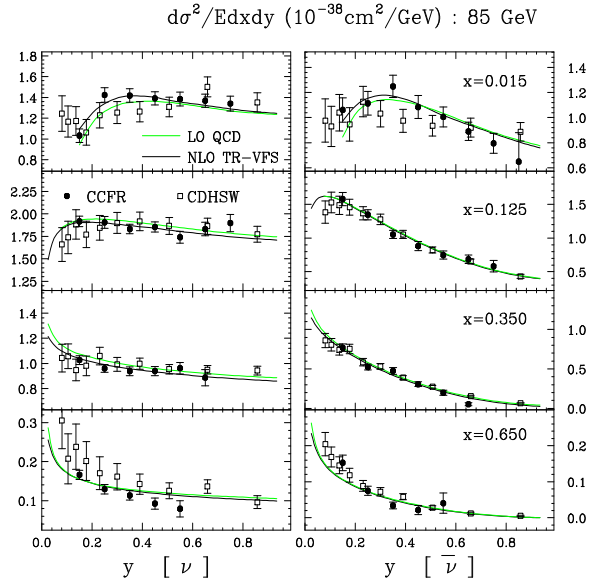


FIG. 1. Some of the CCFR and CDHSW differential cross section data at  $E_\nu = 85$  (both statistical and systematic errors are included). The data are in good agreement with the NLO TR-VFS QCD calculation using MRST99 (extended) PDFs (dashed line). The solid line is a leading order CCFR QCD inspired fit used for acceptance and radiative corrections. A disagreement between the CCFR data and CDHSW data is observed in the slope of the  $y$  distribution at small  $x$ , and in the level of the cross sections at large  $x$ .

The CCFR experiment collected data using the Fermilab Tevatron Quad-Triplet wide-band  $\nu_\mu$  and  $\bar{\nu}_\mu$  beam. The CCFR detector [13] consists of a steel-scintillator target calorimeter instrumented with drift chambers,

followed by a toroidally magnetized muon spectrometer. The hadron energy resolution is  $\Delta E_h/E_h = 0.85/\sqrt{E_h}(\text{GeV})$ , and the muon momentum resolution is  $\Delta p_\mu/p_\mu = 0.11$ . By measuring the hadronic energy ( $E_h$ ), muon momentum ( $p_\mu$ ), and muon angle ( $\theta_\mu$ ), we construct three independent kinematic variables  $x$ ,  $Q^2$ , and  $y$ . The relative flux at different energies, obtained from the events with low hadron energy ( $E_h < 20$  GeV), is normalized so that the neutrino total cross section equals the world average  $\sigma^{\nu N}/E = (0.677 \pm 0.014) \times 10^{-38} \text{ cm}^2/\text{GeV}$  and  $\sigma^{\bar{\nu} N}/\sigma^{\nu N} = 0.499 \pm 0.005$  [14]. After fiducial and kinematic cuts ( $p_\mu > 15$  GeV,  $\theta_\mu < 0.150$ ,  $E_h > 10$  GeV, and  $30 \text{ GeV} < E_\nu < 360 \text{ GeV}$ ), the data sample used for the extraction of structure functions consists of 1,030,000  $\nu_\mu$  and 179,000  $\bar{\nu}_\mu$  events. Dimuon events are removed because of the ambiguous identification of the leading muon for high- $y$  events.

The raw differential cross sections per nucleon on iron are determined in bins of  $x$ ,  $y$ , and  $E_\nu$  ( $0.01 < x < 0.65$ ,  $0.05 < y < 0.95$ , and  $30 < E_\nu < 360$  GeV). Over the entire  $x$  region, differential cross sections are in good agreement with NLO QCD calculation using the Thorne and Roberts Variable Flavor Scheme (TR-VFS) [15] with MRST99 [16] extended [17] PDFs (with  $R = R_{eff}^\nu$ ). This calculation includes an improved treatment of massive charm production. The QCD predictions, which are on free neutrons and protons, are corrected for nuclear [18], higher twist [3,4] and radiative effects [19].

Figure 1 shows some bins of the differential cross sections extracted at  $E_\nu = 85$  GeV (complete tables of the differential cross sections at all other energy bins are available [12]). Also shown are the prediction of the NLO QCD TR-VFS calculation using extended MRST99 PDFs, and the prediction from a CCFR leading order Buras-Gaemers (LO-BG) QCD inspired fit [12] used for calculation of acceptance and resolution smearing corrections (uncertainties in these corrections are included in the systematic errors). As expected from the quark parton model and QCD, the CCFR data exhibit a quadratic  $y$  dependence at small  $x$  for  $\nu_\mu$  and  $\bar{\nu}_\mu$ , and a flat  $y$  distribution at high  $x$  for the  $\nu_\mu$  cross sections. Also shown are differential cross sections reported by the CDHSW [7] collaboration. A disagreement between the CCFR data and CDHSW data is observed in the slope of the  $y$  distribution at small  $x$ , and in the level of the cross sections at large  $x$ . This difference is crucial in any QCD analysis which uses the CDHSW data. For example, at the lowest  $x$  bin the CDHSW  $\nu_\mu$ -Fe data continues to increase with  $y$ , in contrast to the small decrease at large  $y$  which is expected from the antiquark component in the nucleon. In addition, at the highest value of  $x$  ( $x = 0.65$ ), the level of CDHSW  $\nu_\mu$ -Fe data does not agree with CCFR or with the QCD predictions. A recent QCD analysis [20] which includes these CDHSW data, extracts an anomalously large asymmetry between the  $s$  and  $\bar{s}$  quark distribution at high  $x$  from the CDHSW data. Since the  $u$  and  $d$  quark

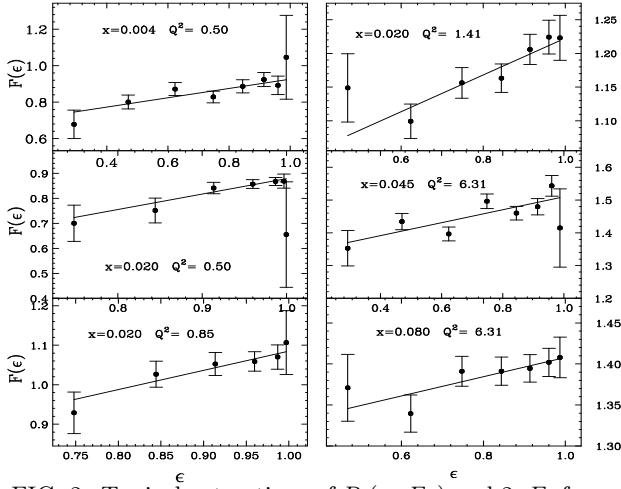


FIG. 2. Typical extractions of  $R$  (or  $F_L$ ) and  $2xF_1$  for representative values of  $x$  and  $Q^2$ .

distributions are very well constrained at this value of  $x$  (from muon data on hydrogen and deuterium), the only way to accommodate the high  $x$  CDHSW data is by the introduction of an asymmetric strange sea at high  $x$ . The CCFR data do not show this anomaly.

The raw differential cross sections are corrected for electroweak radiative effects [19], the  $W$  boson propagator, and for the 5.67% non-isoscalar excess of neutrons over protons in iron (only important at high  $x$ ). Values of  $R$  (or equivalently  $F_L$ ) and  $2xF_1$  are extracted from the sums of the corrected  $\nu_\mu$ -Fe and  $\bar{\nu}_\mu$ -Fe differential cross sections at different energy bins according to Eq. (1). An extraction of  $R$  using Eq. (1) requires a knowledge of  $\Delta xF_3$  term. We obtain  $\Delta xF_3$  from theoretical predictions for massive charm production using the TR-VFS NLO calculation with the extended MRST99 and the suggested scale  $\mu = Q$ . This prediction is used as input to Eq. (1) in the extraction of  $R^\nu$ . This model yields  $\Delta xF_3$  values similar to the NLO ACOT Variable Flavor Scheme [21], (implemented with CTEQ4HQ [22] and the recent ACOT [23] suggested scale  $\mu = m_c$  for  $Q < m_c$ , and  $\mu^2 = m_c^2 + 0.5Q^2(1 - m_c^2/Q^2)^n$  for  $Q > m_c$  with  $n = 2$ ). A discussion of the various theoretical calculations for  $\Delta xF_3$  can be found in references [24,25]. Because of the positive correlation between  $R$  and  $\Delta xF_3$ , the uncertainty in  $\Delta xF_3$  introduces a model systematic error at low  $x$ . However, for  $x > 0.1$ , the  $\Delta xF_3$  term is small, and the extracted values of  $R^\nu$  are not sensitive to  $\Delta xF_3$ . For the systematic error on the assumed level of  $\Delta xF_3$ , we vary the strange sea and charm sea simultaneously by  $\pm 50\%$  ( $\Delta xF_3$  is directly sensitive to the strange sea minus charm sea). Note that the extracted value of  $R$  is larger for a larger input  $\Delta xF_3$  (i.e. a larger strange sea).

Figure 2 shows typical extractions of  $R$  (or  $F_L$ ) and  $2xF_1$  for a few values of  $x$  and  $Q^2$ . The extracted values of  $R^\nu$  are sensitive to the energy dependence of the

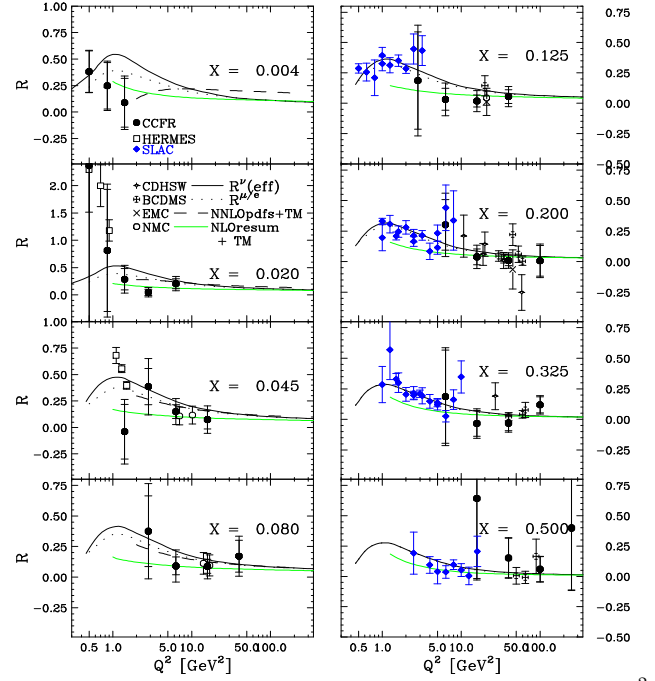


FIG. 3. CCFR measurements of  $R^\nu$  as a function of  $Q^2$  for fixed  $x$ , compared with electron and muon data, with the  $R^{\mu/e}$  and  $R^{\nu}_{eff}$  ( $m_c = 1.3$ ) fits, with  $R^{\mu/e}_{NNLOpdfs+TM}$  QCD calculation including NNLO PDFs (dashed), and with  $R^{\mu/e}_{NNLOresum+TM}$  (dotted). The inner errors include both statistical and experimental systematic errors added in quadrature. The outer errors include the additional  $\Delta xF_3$  model errors (added linearly). Also shown are the HERMES results for  $R^e_{N14}$  at small  $x$  and  $Q^2$ .

neutrino flux ( $\sim y$  dependence), but are insensitive to the absolute normalization. The uncertainty on the flux shape is estimated by constraining  $F_2$  and  $xF_3$  to be flat over  $y$  (or  $E_\nu$ ) for each  $x$  and  $Q^2$  bin.

The extracted values of  $R^\nu$  are shown in Fig. 3 for fixed  $x$  versus  $Q^2$ . The inner errors include both statistical and experimental systematic errors (of similar magnitude on average [12]) added in quadrature. The outer errors include the additional  $\Delta xF_3$  model errors (added linearly). At the very lowest  $Q^2$  values, the model error is reduced because all models for  $\Delta xF_3$  approach zero around  $Q^2 = 0.4$  GeV<sup>2</sup>. This is because the strange quark distribution is expected to approach zero for  $Q$  values close to twice the mass of the strange quark. In addition, the very low  $Q^2$  region is below charm production threshold. Note that the very low  $Q^2$  and low  $x$  region is of interest because it is where HERMES reports [5] an anomalous increase in  $R^e$  for nuclear targets.

The CCFR  $R^\nu$  values are in agreement with measurements of  $R^{\mu/e}$  [8,9,26–28], and also in agreement with both the  $R^{\mu/e}_{world}$  and  $R^{\nu}_{eff}$  fits. At low  $x$ , the data are lower than the extrapolated values from these two fits. Also shown in Fig. 3 and Fig. 4 are the two most recent calculations  $R^{\mu/e}_{NNLOpdfs+TM}$  (dashed line) and

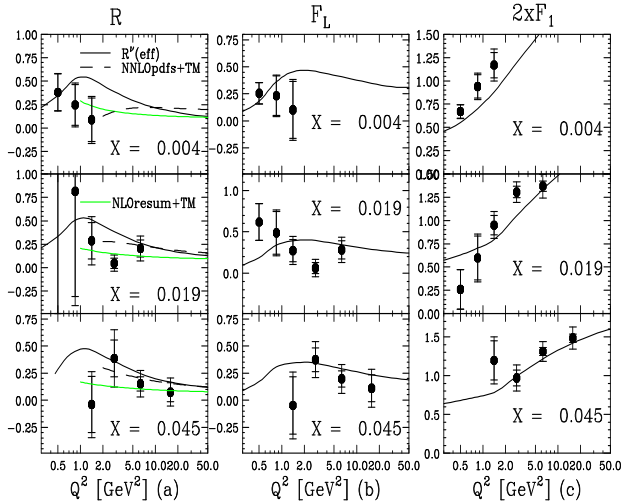


FIG. 4. CCFR measurements of  $R$  (a),  $F_L$  (b) and  $2xF_1$  (c) data as a function of  $Q^2$  for  $x < 0.05$ . The curves are the predictions from a QCD inspired leading order fit to the CCFR differential cross section data  $R = R_{eff}^\nu$ . Also shown is the  $R_{NNLOpdfs+TM}^{\mu/e}$  QCD calculation including NNLO PDFs (dashed) and  $R_{NLOresum+TM}^{\mu/e}$  (dotted).

$R_{NLOresum+TM}^{\mu/e}$  (dotted line). Note that a complete calculation should include both the NNLO and the  $\ln(1/x)$  resummation terms. The calculations including either of these higher order terms yield values of  $R$  at small  $x$  and low  $Q^2$  which are lower than  $R_{world}^{\mu/e}$ , and are in better agreement with the data. However, at low  $x$  for  $Q^2 < 5$  GeV<sup>2</sup> there are large uncertainties in  $R_{NNLOpdfs+TM}^{\mu/e}$  (mostly from the NNLO gluon distribution).

Also shown are the HERMES electron scattering results in nitrogen at low values  $x$ . The HERMES data [5] for  $R$  are extracted from their ratios for  $R_{N14}/R_{1998}$  by multiplying by the values from the  $R_{1998}$  fit [26]. The CCFR data do not clearly show a large anomalous increase at very low  $Q^2$  and low  $x$ . It is expected that any nuclear effect in  $R$  would be enhanced in the CCFR iron target with respect to the nitrogen target in HERMES. However, depending on the origin, the effects in electron versus  $\nu_\mu$  charged current scattering could be different.

The CCFR measurements of  $F_L$  and  $2xF_1$  as a function of  $Q^2$  for  $x < 0.05$  are shown in Fig. 4. The curves are the predictions from a QCD inspired leading order fit to the CCFR differential cross section data with  $R = R_{eff}^\nu$ . The extracted values at the very lowest  $x$  and  $Q^2$  do not show any anomalous increase in  $R$  in our iron target. At the lowest values of  $x$ , the disagreement between the QCD inspired fit and the data is because  $R = R_{eff}^\nu$  was assumed (but our data and the most recent theoretical calculations favor smaller values of  $R$  in this region).

In conclusion, over the  $x$  and  $Q^2$  range where perturbative QCD is expected to valid,  $R^\nu$  is in good agreement with  $R^{\mu/e}$  data, and with the NNLO QCD calculation including NNLO PDFs and target mass effects. A very

large nuclear enhancement in  $R$  (as reported by the HERMES experiment for electron scattering on nitrogen) is not clearly observed in  $\nu_\mu$ -Fe scattering. A comparison between CCFR and CDHSW differential cross section indicates that although the cross sections agree over most of the kinematic range, the CCFR data do not show the deviations from the QCD expectations that are seen in the CDHSW data at very low and very high  $x$ .

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